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ATMOSPHERIC TEMPERATURE CHANGES ASSOCIATED WITH HIGH ALTITUDE TURBULENCE

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16. Abstract

Previous research has indicated a correlation between atmospheric temperature changes and clear air turbulence in the upper troposphere and lower stratosphere. Data from 13 XB-70 test flights and military training flights were analyzed in conjunction with information compiled on commercial flights to further explore the temperature-turbulence relationship. Three cases were discussed in detail in which significant high altitude turbulence was encountered. This analysis revealed that horizontal temperature gradients of 1.0°C per 10 nautical miles depicted on meteorological constant pressure charts are indicative of moderate turbulence. Furthermore, changes in isotherm orientation of 45° or more between two successive mandatory constant pressure levels appear to be related to similar intensities of clear air turbulence.

This information together with vertical temperature profile criteria will hopefully contribute to the successful development of remote sensing devices to detect clear air turbulence in the stratosphere.

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FOREWORD

Collecting meteorological data on commercial jet flights that coincided as closely as possible to the time and ground track of XB-70 test flights and military aircraft training flights was one of the requirements of this research study. Since these flights were conducted over the Western United States, it was necessary to request authorization from several airlines for the privilege of admission to the flight deck for this purpose.

Eastern Air Lines Flight Research & Development Department would like to express their sincere appreciation to the following airlines for granting this request and to the flight crews for cooperating in the data collection.

Flight Operations Department - Continental Airlines, Inc.
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Flight Operations Department - United Air Lines, Inc.
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Furthermore, Eastern Air Lines is indebted to and wishes to thank Headquarters Strategic Air Command, 9th Strategic Reconnaissance Wing, 3rd Weather Wing, and the SAC flight crews for their support in providing the valuable pilot reports from their operational organizations.

In addition, the support of Mr. L. J. Ehernberger, Flight Research Center, National Aeronautics and Space Administration, Edwards, California for counselling and guidance during the term of this study is gratefully acknowledged.

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SUMMARY

The frequency of reports of significant turbulence in the stratosphere indicates a requirement for developing forecasting procedures and remote detection systems that will assist flight crews in supersonic aircraft in avoiding this phenomenon. Earlier research has revealed the possible relationship between several features of atmospheric behavior and clear air turbulence. This study investigated, primarily, the association between horizontal and vertical temperature gradients in the atmosphere and flight conditions reported by supersonic aircraft. Meteorological data compiled on coincidental jet flights were analyzed in conjunction with information from eight XB-70 test flights and five military training flights to explore the temperature-turbulence relationship. In-flight data from commercial aircraft instrumentation and visual observations of sky conditions were recorded by a research meteorologist which, in addition to information received from other aircraft, provided a more complete description of the atmosphere for research analysis.

Horizontal isotherm patterns observed on meteorological upper air charts in which certain magnitudes of temperature changes were related to distance criteria indicated that a 1.0°C temperature change in 10 nautical miles was associated with moderate turbulence. Larger temperature gradients indicated higher intensities of turbulence while smaller gradients were associated with smooth air or light turbulence. A change in isotherm orientation between two successive mandatory constant pressure levels that exceeded 45° was also found to be associated with high altitude turbulence. These temperature criteria have been used in conjunction with vertical temperature profile analyses to aid in describing potential areas of clear air turbulence at the higher altitudes.

It is anticipated that the temperature gradients analyzed on a mesoscale basis, which show a relationship to high altitude turbulence, could also be explored in microscale with remote sensing devices such as radiometers or other sensitive electronic equipment.

INTRODUCTION

The increasing number and frequency of aircraft operating in the stratosphere is directly related to the increasing volume of clear air turbulence reports received from high altitude aircraft. This fact has augmented research activity associated with the development of improved forecast procedures and, equally important, a practical airborne remote detection device. Investigations to discover which meteorological parameters are associated with clear air turbulence have revealed several features of atmospheric behavior that warrant further exploration. For example, Haymond (Ref. 1) discovered that clear air turbulence in the stratosphere could be forecast with greatly improved accuracy utilizing certain temperature inversion criteria. As a result of evaluating forecasts for U-2 flights, he found that temperature inversions of 1.5° to 2.5°C per thousand feet were associated with light turbulence. A 2.5° to 4.0°C/1000 feet temperature change indicated moderate turbulence. An inversion in which the temperature changed at a rate exceeding 4.0°C/1000 feet as determined from the radiosonde was normally indicative of shallow layers of severe clear air turbulence at the levels of the large inversions.

Mitchell (Ref. 2), in an analysis of 106 WU-2 flights, suggested the relationship between horizontal and vertical temperature gradients and encounters of clear air turbulence shown in Table 1.

TABLE 1. HORIZONTAL AND VERTICAL TEMPERATURE GRADIENTS VERSUS CAT

	Horizontal	Vertical	Turbulence
Small Temp. Gradient	< 1° C/25nm	* (±) < 1-1 1/2°C/1000'	VL - Smooth
Medium Temp. Gradient	1°C/25nm to 1°C/12nm	(±) 1-1 1/2°C to 2-2 1/2°C/1000'	Lt. - Mod.
Large Temp. Gradient	> 1°C/12nm	(±) > 2 1/2°C/1000'	Mod. - Severe

* Added for clarity, with the author's permission.

The vertical temperature gradients from radiosonde data applied to large lapse, as well as large inversion rates.

Ehernberger (Ref. 3) in an earlier analysis of data from 36 XB-70 flights found that the occurrence of significant turbulence was often related to a number of synoptic and upper air features which included vertical temperature gradients, wind velocity, and vertical wind shear parameters for layers at, as well as below, the flight level of the aircraft.

The author's previous flight experience has revealed that a relationship exists between fine scale atmospheric temperature gradients and the encounter of significant clear air turbulence (Kadlec, Ref. 4). Therefore, an examination was initiated to determine the value of detailed temperature gradient measurements from subsonic commercial flights for the investigation of turbulence at altitudes from the tropopause to 50 mb (68,000 feet). The investigation utilized two methods of approach. First, detailed microscale aircraft temperature measurements were made for comparison with horizontal temperature gradients determined from upper air mesoscale analyses and with turbulence encounters in the lower stratosphere. The second approach included mesoscale analyses of meteorological horizontal and vertical temperature patterns associated with high altitude flight conditions.

Data were obtained from the National Aeronautics and Space Administration Flight Research Center XB-70 test program as well as pilot reports from U.S. Air Force aircraft. In addition, a research meteorologist, riding as an extra crew member in the cockpit of commercial aircraft, completed 28 flights over the Western United States to collect data on certain days that were coincidental to flights of the XB-70 and military aircraft. These flights are listed in the Appendix according to date, route, flight number, and flight times.

DATA ACQUISITION AND EVALUATION

The inflight collection of all pertinent information available from cockpit instrumentation and visual observations of sky conditions by the research meteorologist provided the primary source of data for analysis. These data were recorded on horizontal and vertical cross sections which included information on route, altitude, location, time, flight conditions, sky conditions, temperature, airspeed, Mach number, wind component, weather radar returns, and pilot reports from other aircraft. Meteorological horizontal and vertical cross sections utilizing radiosonde information including pressure, temperature, and winds were prepared in conjunction with these data to assist in the analysis and interpretation of temperature gradients reported inflight and their association with turbulence at higher altitudes. Radiosonde data were selected and plotted on adiabatic charts to coincide as closely as possible to both the time and areas of each individual supersonic flight. Then a comparative analysis was made of these data and the criteria indicated by the previously mentioned authors. (Ref. 1, 2, 3, 4.)

Horizontal temperature gradients were measured on the commercial subsonic flights to further refine the relationship between certain temperature changes and the occurrence of significant turbulence. It had previously been established that a rate of horizontal temperature change equaling or exceeding 1.0°Celsius per minute in conjunction with a total change of temperature of at least 3.0°C at this rate was associated with significant turbulence that occurred in clear skies. These values apply to the subsonic cruising airspeed range between Mach .82 and .85. They were the minimum found to be useful, although faster rates and larger total amounts of change generally indicated higher intensities of turbulence.

RESULTS

During the period of this study, pilot reports were received from supersonic aircraft which included information on flight conditions ranging from smooth to moderate turbulence. Case studies of three situations in which moderate turbulence was reported on one or more occasions have been selected for a more detailed analysis.

Case No. 1 - January 12, 1968

The XB-70 completed a test flight over the Western United States in which supersonic airspeeds were attained in the stratosphere on January 12, 1968. During supersonic acceleration above 35,000 feet at 1840Z, the aircraft encountered light, increasing to moderate turbulence between 38,000 and 40,000 feet northwest of Coaldale, Nevada at Mach 1.5 to 1.7. Above 60,000 feet, at Mach 2.5, the flight was essentially in smooth air, although the pilots reported "some smooth vertical air movements which made speed stabilization difficult". Military supersonic aircraft operating above 50,000 feet also reported smooth flight conditions from the Continental Divide to California.

The surface weather chart at 1800Z revealed the presence of a large high pressure center located over Northeastern Utah and Southwestern Wyoming. Weak mountain wave activity was present over the Sierra Nevada Mountains. Lenticular clouds were observed to extend along the eastern slopes of the mountains from the Owens Valley north to Reno, Nevada. A polar jet stream oriented northwest-southeast over the Continental Divide at 1200Z moved to the Western Dakotas by 0000Z/13. Maximum wind velocities varied between 90 and 105 knots at core level near 34,000 feet.

The commercial flight on the route from Los Angeles to Seattle via Reno, Nevada and Lakeview, Oregon did not encounter any horizontal temperature changes greater than 0.5°C/minute. Furthermore, no turbulence greater than very light chop was encountered at Flight Level 390, between 1750 and 1915Z. During the time of the commercial flight the Oakland tropopause lifted from an altitude of 37,400 feet at 1200Z/12 to 41,300 feet at 0000Z/13. Also, in the area of the XB-70 flight, the tropopause at Yucca Flat and Winnemucca, Nevada at these times was at 39,000 feet or above. Although a few lenticular clouds associated with apparent weak mountain wave activity were present, the commercial flight did not encounter turbulence in connection with the wave even though the aircraft was probably within 1,000 feet of the tropopause.

The return southbound commercial flight from Seattle to Los Angeles at Flight Level 370 encountered light chop beginning 65 nautical miles south of Lakeview, Oregon and extending to the point of descent 35 nautical miles north of Bakersfield, California. No reduction in cruising airspeed to minimize the turbulence was required. The flight was just below the bases of a broken to overcast cirrus layer and the tropopause inversion. No horizontal temperature changes greater than 0.2°C/minute were encountered on this flight while at cruising altitudes between 2100 and 2225Z. Weak mountain wave activity was present along the route similar to that experienced on the northbound flight. The capability of comparing inflight data from more than one aircraft is an important requirement in research of this nature. In this case, two aircraft experienced significantly different flight conditions although they were within 60 nautical miles of each other and less than 30 minutes apart in time when the XB-70 encountered turbulence. Although the XB-70 is somewhat larger than the Boeing 720-B on the commercial flight, of more importance is the difference in airspeed between the two aircraft. The XB-70 was accelerating during climb at an airspeed near Mach 1.5 at 38,400 feet when moderate turbulence was encountered passing through the tropopause. The northbound Boeing 720-B was cruising at Mach .84 at 39,000 feet. Evaluation of turbulence reports from various aircraft must consider the possible differences in reported intensities resulting from aircraft of different sizes and weights operating at significantly different airspeeds.

Radiosonde reports in the area of the XB-70 track revealed significant variations in the vertical temperature profile at several stations. The Vandenberg Air Force Base, California raob displayed a tropopause at 39,900 feet with a lapse rate of -0.5°C/1000 feet at 1200Z, January 12. However, at 0000Z/13, the characteristic of the tropopause which had lowered slightly to 38,100 feet changed to a shallow but pronounced inversion with an increase in temperature of +6.1°C/1000 feet. Vertical wind shear at the altitude of the tropopause decreased from 6.5 knots/1000 feet at 1200Z/12 to 2.6 knots/1000 feet at 0000Z/13. The Oakland, California raob revealed a similar change in tropopause characteristic. At 1200Z/12, a lapse rate of -0.7°C/1000 feet was observed at 37,400 feet. Twelve hours later the tropopause increased in height to 41,300 feet with a sharp inversion of +5.2°C/1000 feet. The vertical wind shear at the tropopause also increased from 3.6 knots/1000 feet at 1200Z/12 to 8.5 knots/1000 feet at 0000Z/13. There was no significant directional wind shear in this layer of reported moderate turbulence.

Yucca Flat and Winnemucca raobs both displayed tropopause inversion rates of +1.5°C/1000 feet or less at 1200Z/12 and 0000Z/13. At these same times, the altitude of the tropopause at these stations varied between 39,000 and 41,600 feet. Since moderate turbulence was encountered during the climbout portion of the flight, horizontal temperature measurements could not be made from the recorded data.

The remainder of the XB-70 test flight was conducted at flight altitudes between 60,000 and 67,000 feet. The 70 mb (61,000 feet) and the 50 mb (68,000 feet) constant pressure charts, as well as the horizontal temperature and wind, and vertical temperature and wind cross sections, were analyzed to determine if any information from these sources would indicate possible turbulence. However, none of these charts revealed any information that would result in a forecast of significant turbulence in the stratosphere. Furthermore, no significant temperature changes were recorded by the XB-70 when cruising altitude and airspeed remained constant. Horizontal temperature data were not reported by any of the military aircraft. Therefore, in this case, the XB-70 encountered turbulence as it penetrated the tropopause, probably in an area associated with weak mountain wave activity.

Case No. 2 - June 27, 1968

Data for this case study were received initially in the form of military pilot reports of moderate turbulence at supersonic airspeeds over Eastern Idaho between 50 and 55,000 feet near 1900Z on June 27, 1968. Another aircraft reported several encounters of moderate turbulence between 1830 and 2000Z/27 in the same general area but at altitudes from 37,000 to 57,000 feet.

An XB-70 flight was scheduled for this day; however, mechanical problems forced cancellation of the test. Since the commercial flight had already departed, data were recorded in the usual manner in anticipation of making a comparative study if other aircraft reported significant turbulence over the western mountain region of the United States. Military aircraft operating over Idaho did report turbulence, although the area was over 300 nautical miles east of the commercial flight track. However, information from the commercial flight was useful in determining the extent of the turbulence area and the association between meteorological and flight conditions.

On the surface chart, a weak cold front extended northeast-southwest across West-central Montana, Central Idaho, Northern Nevada and California at 1200Z/27 with a Pacific High centered west of the California-Oregon coast. No precipitation was observed along the front over Idaho. The polar jet stream was oriented approximately east-west near the United States-Canadian border with a maximum wind velocity of 115 knots. The altitude of the jet stream varied between 35,000 feet along the Northwest Washington coast to 39,000 feet over Northern Montana. Figure 1 depicts the relative position of the turbulence reports between 1830 and 2000Z/27, as well as the surface front and jet stream position at 1200Z/27. The track of the round trip commercial flight from Los Angeles to Seattle is also shown.

The comparative commercial flight between Los Angeles and Seattle did not encounter any turbulence at Flight Level 350 between 1710 and 1825Z. The Seattle-Los Angeles flight was also smooth while cruising at Flight Level 370 from 2005 to 2115Z. The maximum horizontal temperature gradient that was measured on both flights was 0.3°C/minute . The flights

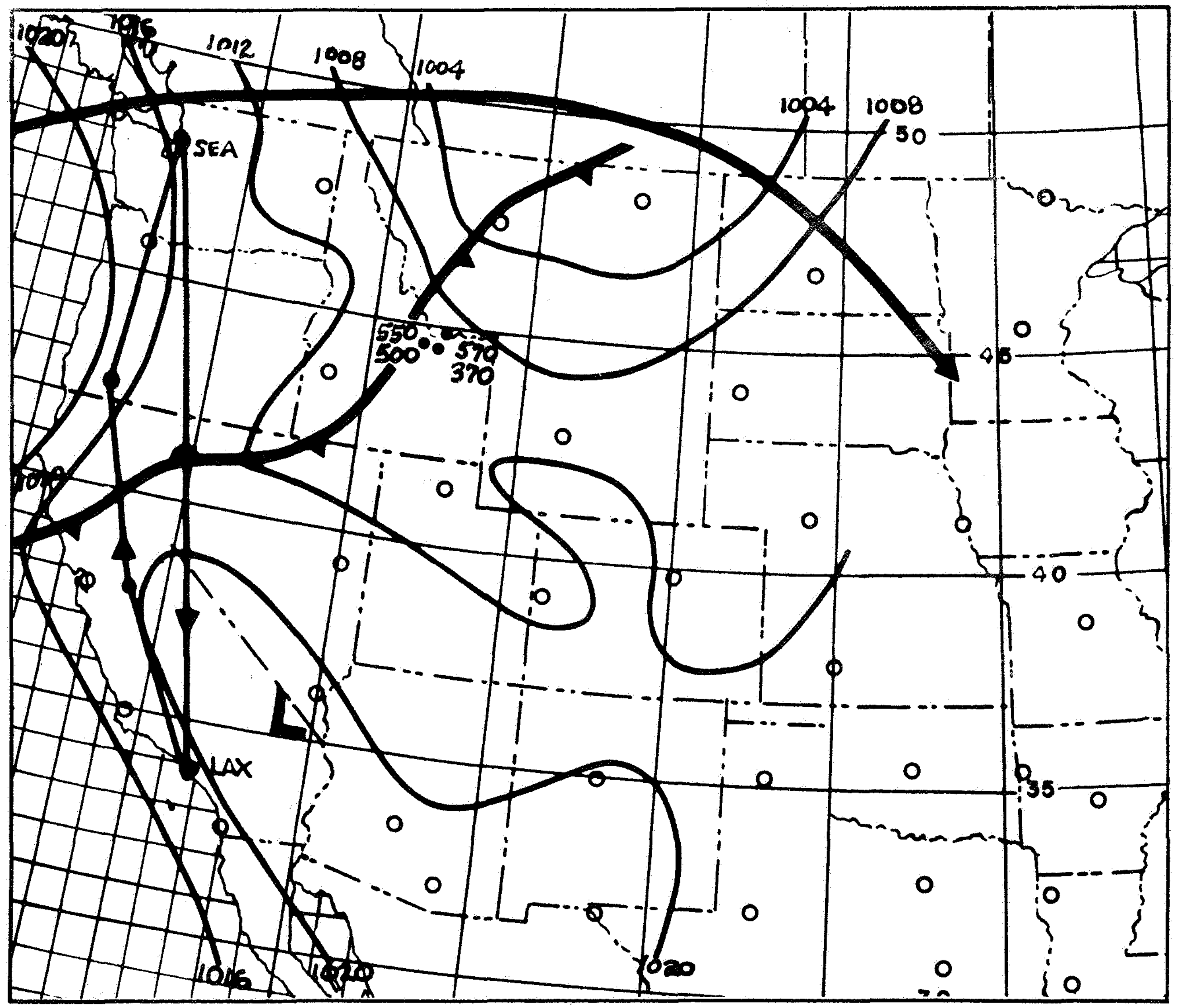

FIGURE 1. Surface Front and Jet Stream Locations, 1200Z June 27, 1968
Turbulence Reports, 1830 - 2000Z/27
Commercial Flight Tracks, 1740 - 2250Z/27

were in the clear at all times while at their respective cruising altitudes with only lower broken to overcast clouds below 15,000 feet over Oregon and Washington. No indications of mountain wave activity were observed although the 1200Z wind direction at 18,000 feet over Idaho in the area of turbulence was 260° at 36 knots.

Analysis of the 150 mb (45,000 feet) and 100 mb (53,000 feet) horizontal temperature and wind field provided a possible clue to the turbulence that was encountered by the supersonic aircraft. Over Central Idaho and Southern Montana, at the 150 mb level, a horizontal temperature change of 1.0°C in 50 nautical miles was observed at 1200Z/27 in the area of reported turbulence. At 0000Z/28, the horizontal gradient increased to 1.0°C in 15 nautical miles in the same area. In this case, the encounter of turbulence occurred near the south but colder temperature side of the isotherm gradient as indicated in Figure 2. The 100 mb constant pressure chart displayed a similar temperature change pattern. At 1200Z/27, the isotherm gradient in the turbulent area equalled 1.0°C in 50 nautical miles. Twelve hours later, the gradient increased 1.0°C in 20 nautical miles.

Another feature of the isotherm pattern that was found to be associated with this occurrence of moderate turbulence is revealed in Figure 3. A distinct change in isotherm orientation appears between the 1200Z/27, 150 and 100 mb constant pressure levels in the area of reported turbulence. The turbulence reports were received from that area of the map where the isotherm pattern assumed a change in orientation of 45° or more between the two constant pressure levels. Although the exact aircraft altitude is not known, pilot reports indicated that no turbulence was encountered over Eastern Montana and Western North Dakota above 45,000 feet. This coincides with the area of near parallel orientation of the isotherms. The directional change in isotherm orientation also coincides with those radiosonde stations that reported significant inversions above the tropopause.

Upper winds at both the 150 and 100 mb levels were nearly parallel to the isotherm pattern. A minor southward shift of the polar jet stream of less than 100 nautical miles in 12 hours was observed in conjunction with these significant changes in the horizontal temperature gradient. However, the wind velocity increased nearly 40 knots at the altitude of the turbulent area. No mountain wave activity was reported or observed, although the 500 mb winds at 1200Z/27 indicated west to west-southwesterly flow over the Continental Divide with velocities greater than 35 knots. Convective activity along the weak front was also absent.

Radiosondes near the reported area of turbulence as well as those near the ground track of the commercial flight were plotted to determine the characteristics of the vertical temperature profiles. At 1200Z/27, the Boise, Idaho, Lander, Wyoming, and Great Falls, Montana raobs all displayed pronounced tropopause inversions below 100 mb as shown in Figure 4. The Boise temperature inversion at the tropopause was +2.2°C/1000 feet between 49,800 and 52,500 feet at 1200Z/27. Twelve hours later the tropopause inversion lowered in height to 42,900 feet with a temperature change of +1.4°C/1000 feet up to 46,400 feet. The vertical wind shear at 1200Z between 47 and 50,000 feet was 8.3 knots/1000 feet and 2.2 knots/1000 feet between 50,000 and 53,100 feet. At 0000Z/28 there was no vertical

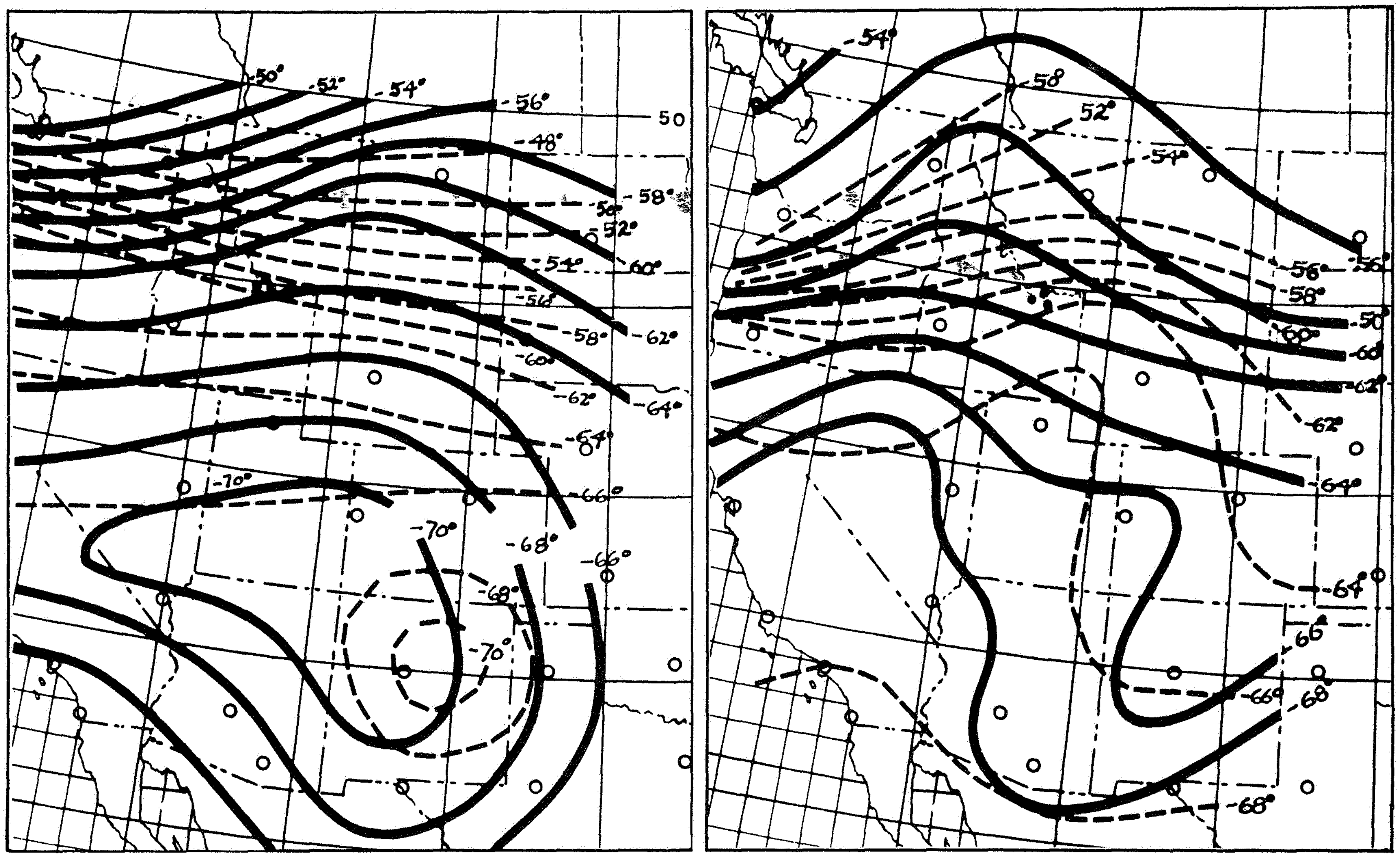

FIGURE 2. 150 MB (Left) and 100 MB (Right) Constant Pressure Levels

1200Z Isotherms ━━━ June 27, 1968
0000Z Isotherms — — — June 28, 1968

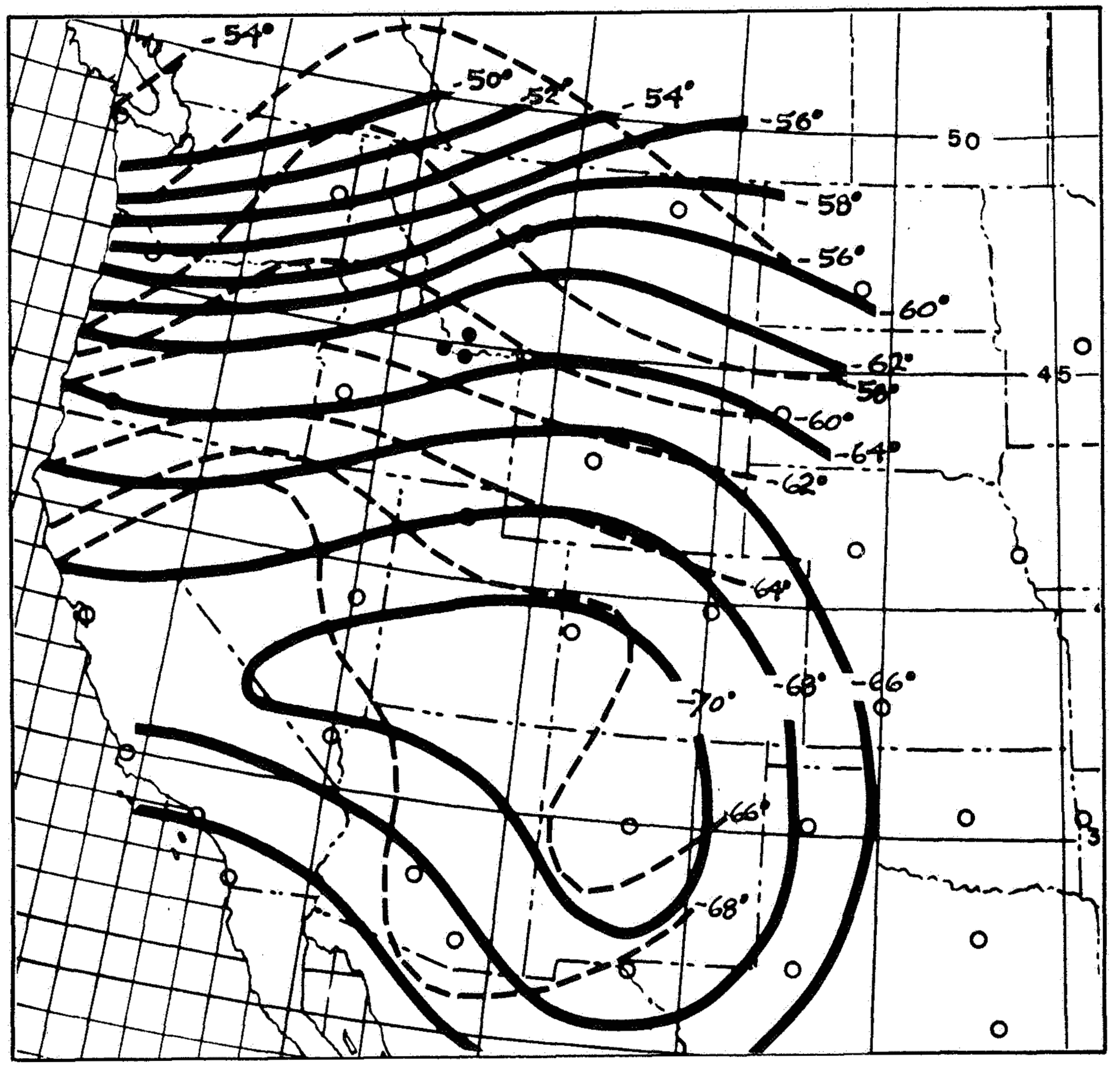

FIGURE 3. 150 MB and 100 MB Constant Pressure Levels, 1200Z June 27, 1968

150 MB Isotherms
100 MB Isotherms

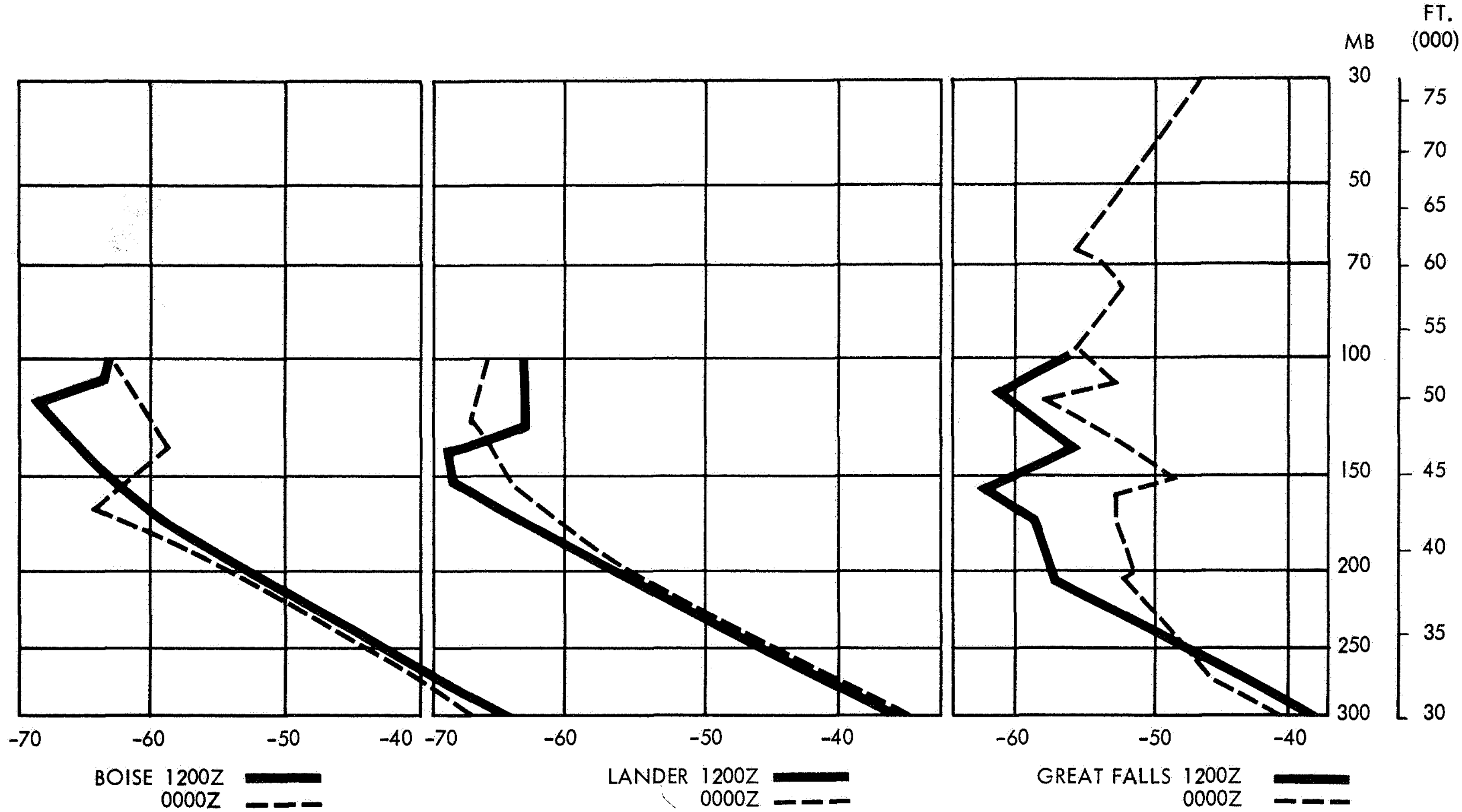

FIGURE 4. Vertical Temperature Profiles for Boise, Lander, and Great Falls

1200Z June 27, 1968
0000Z June 28, 1968

shear between 42,900 and 44,600 feet. Directional wind shear was 10^{o} or less at both raob times.

Great Falls displayed a tropopause inversion at 1200Z of +2.5°C/1000 feet between 44,100 and 47,000 feet which became a sharp inversion of +4.4°C/1000 feet between 43,600 and 44,600 feet twelve hours later. The vertical wind shear between 45 and 50,000 feet was 13 knots/1000 feet at 1200Z and 9.1 knots/1000 feet between 42 and 49,000 feet at 0000Z/28 with no directional shear. A second inversion at 1200Z/27 of +2.0°C/1000 feet between 50,900 and 53,100 feet also appeared at 0000Z/28 with a temperature increase of +3.6°C/1000 feet between 50,200 and 51,700 feet. In this layer, the vertical wind shear was 2.0 knots/1000 feet at 1200Z/27 and 1.3 knots/1000 feet at 0000Z/28 with no directional shear. No significant inversions or lapse rates appeared above 100 mb (53,100 feet).

The tropopause at Lander displayed a pronounced change in characteristic compared to Boise and Great Falls. At 1200Z/27, a tropopause inversion of +3.8°C/1000 feet between 47,200 and 48,900 feet changed to a lapse rate of -0.5°C/1000 feet between 45,200 and 48,900 feet at 0000Z/28. The vertical wind shear at 1200Z was 0.2 knots/1000 feet in a layer between 44,600 and 50,000 feet. At 0000Z/28 the vertical shear between 45,200 and 50,000 feet was 3.3 knots/1000 feet.

In this significant case, it may be concluded that the rather deep layer of turbulence was associated with several temperature and wind shear parameters. Furthermore, rapid changes in these features were observed to occur within the 12 hour period of successive radiosonde reports. Pronounced changes in the horizontal and vertical temperature gradients were the most outstanding meteorological features that could be remotely detected with airborne sensing devices.

Case No. 3 - December 13, 1968

The third case study also involved a report of turbulence by a military supersonic aircraft that occurred at 2100Z on December 13, 1968. Moderate clear air turbulence was encountered during climbout, beginning at and extending above 62,000 feet, approximately 25 nautical miles southeast of Bozeman, Montana.

A weak stationary front oriented northwest-southeast across Western Montana at 1200Z/13 separated two large high pressure areas located over Central Saskatchewan and Southwestern Wyoming. At the same time a Pacific low pressure center was located approximately 500 nautical miles west of the Washington-Oregon Coast as shown in Figure 5. The polar jet stream at 1200Z/13 was oriented northwest-southeast along a Great Falls – Lander line with maximum wind velocities at 130 knots. Twelve hours later, it had moved eastward to a Glasgow, Montana-Rapid City, South Dakota line, with approximately the same maximum wind velocities.

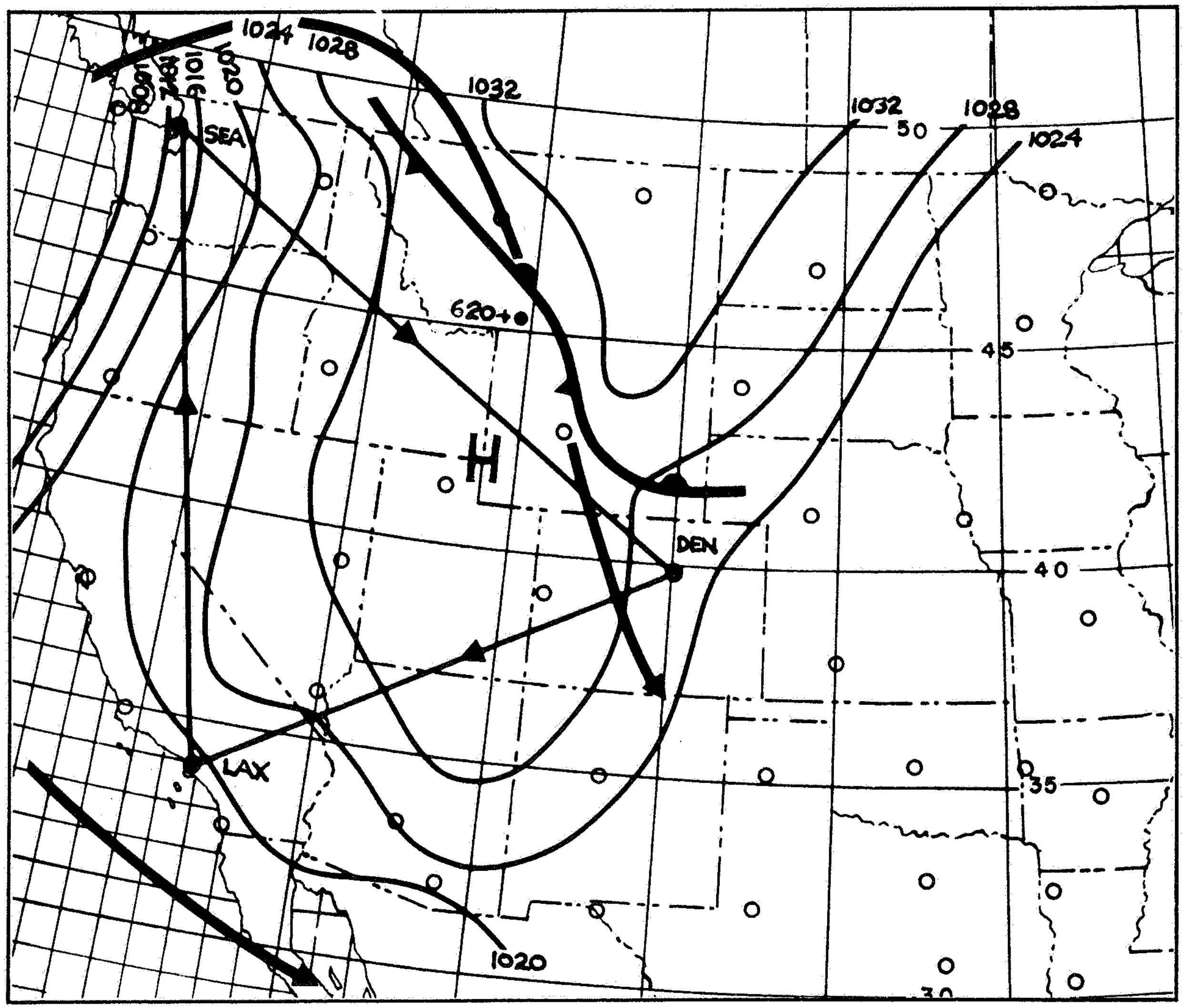

FIGURE 5. Surface Front and Jet Stream Locations, 1200Z December 13, 1968
Turbulence Report, 2100Z/13
Commercial Flight Track SEA - DEN, 2025 - 2220Z/13

The commercial flight from Seattle to Denver at Flight Level 370 between 2045 and 2205Z did not encounter any turbulence. Horizontal temperature changes at cruising altitude were less than 0.1°C/minute. During climbout and at cruising altitude from 50 nautical miles west of Pendleton, Oregon to approximately 50 nautical miles west of Pocatello, Idaho, the flight was on instruments but within 3,000 feet of the tops of a cirrus overcast. The cloud layers and lower level precipitation were associated with the Pacific storm. Therefore, it was impossible to observe lower cloud formations, especially lenticular clouds that might have been associated with mountain wave activity. From Pocatello eastward to Denver, the flight was in thin cirrus or clear skies with no lower clouds below 20,000 feet. While at cruising altitude, the aircraft was at least 6,000 feet below the tropopause at all times.

The lower level 500 mb (18,000 feet) wind field displayed a pronounced wind shift from northwesterly flow at 30 knots or more to southwesterly flow at similar velocities between 1200Z/13 and 1200Z/14. Weak to moderate mountain wave activity was possible during the time of the turbulence encounter which could produce the magnitude of rough air reported by the military aircraft.

The 70 mb (61,000 feet) and 50 mb (68,000 feet) data for 0000Z/14 were analyzed to determine if pressure, temperature, or wind data would reveal a significant pattern that might be associated with the occurrence of turbulence. Horizontal temperature patterns at both 70 and 50 mb revealed an isotherm ridge extending nearly north-south over Idaho and Eastern Nevada-Western Utah as illustrated in Figure 6. The horizontal gradient in the area of turbulence was 1.0°C/65 nautical miles which was insignificant as far as indicating possible turbulence according to the criteria in Table 1.

In this case, only one vertical temperature profile displayed the rather characteristic inversion often associated with turbulence. Between 64,800 and 67,100 feet, the 0000Z/14 Lander raob showed an inversion of +2.0°C/1000 feet as shown in Figure 7. The vertical wind shear between 61 and 65,000 feet was less than 1.0 knot/1000 feet; however, the directional shear was 30° between these layers.

At 1200Z/13, only the Great Falls raob showed a significant temperature inversion. An increase of +2.3°C/1000 feet between 62,900 and 66,100 feet indicated light turbulence according to the Haymond criteria. However, at 0000Z/14 this inversion disappeared at the same time the more pronounced inversion appeared at Lander.

No conclusive association between observed meteorological conditions and the reports of turbulence is revealed in this case. Further research is required to determine the effect of even weak mountain wave activity on flight conditions in the stratosphere.

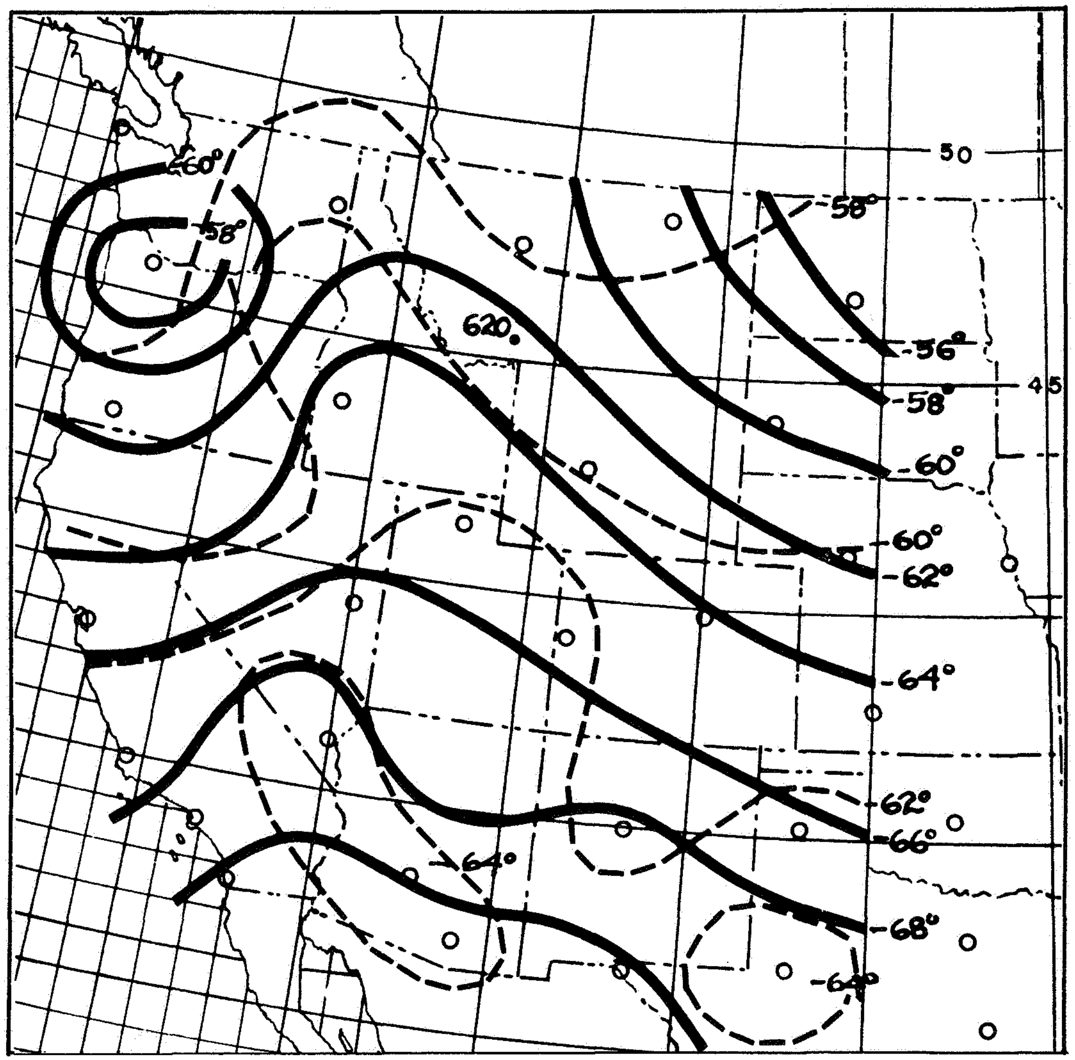

FIGURE 6. 70 MB and 50 MB Constant Pressure Levels, 0000Z December 14, 1968

70 MB Isotherms
50 MB Isotherms

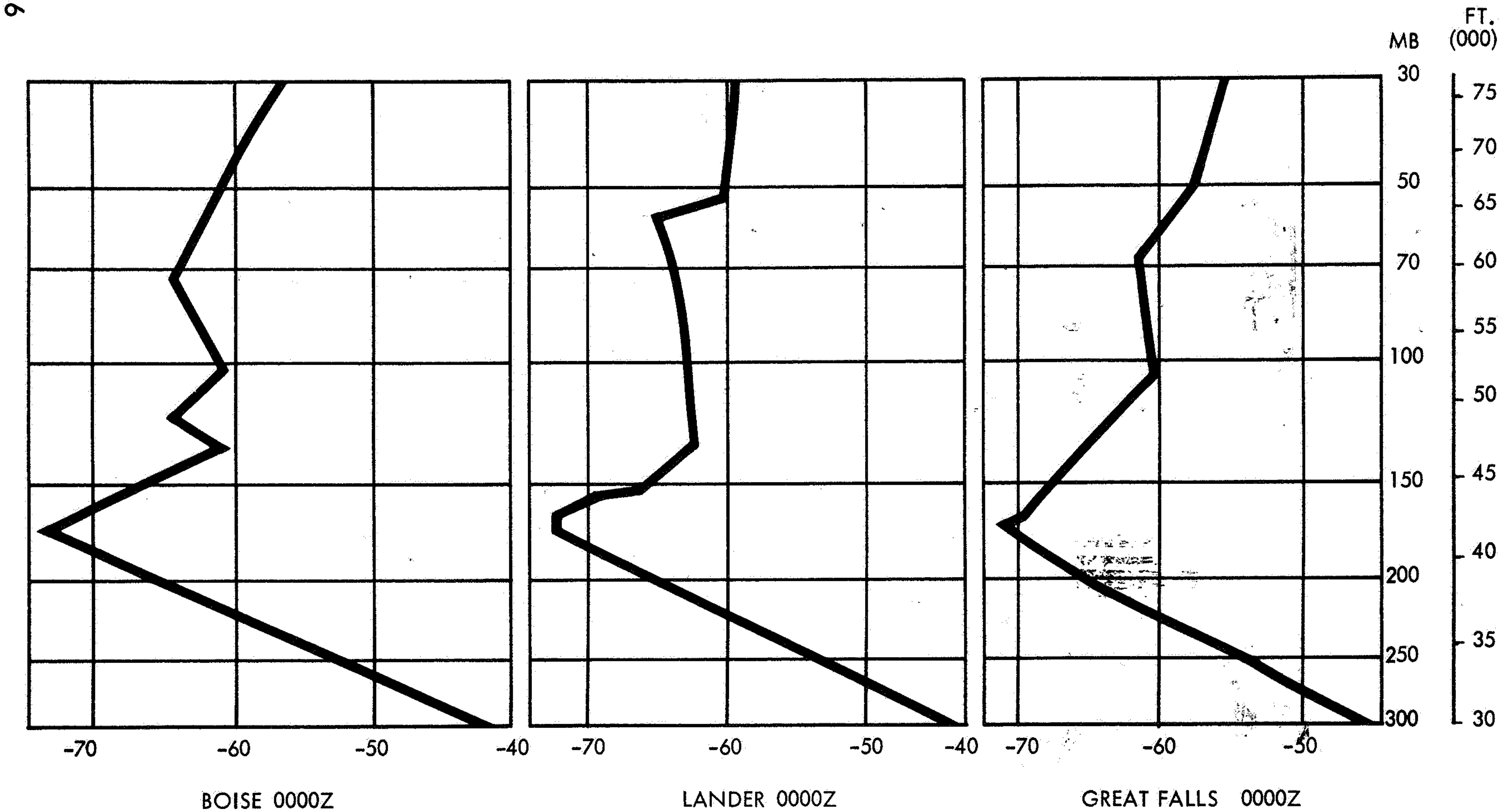

FIGURE 7. Vertical Temperature Profiles for Boise, Lander, and Great Falls

0000Z December 14, 1968

DISCUSSION

Of the 13 flights or cases analyzed during the period of this study, only two reported moderate turbulence in the stratosphere. These were reported by military aircraft which also submitted information on one additional moderate encounter that occurred on descent below the tropopause. Only one incident of moderate turbulence, which occurred during climb, was reported by the XB-70, although several light and very light turbulence occurrences were experienced on other flights. However, it should be noted that XB-70 test flights were normally planned to avoid adverse weather. Therefore, the incidence of significant turbulence from this vehicle may have been somewhat less than might be expected from operational military or commercial supersonic aircraft.

The analysis of flight and meteorological data revealed two horizontal temperature behavior patterns that were observed to occur in conjunction with one of the encounters of moderate clear air turbulence in the lower stratosphere. These patterns might prove useful in further defining forecast areas of turbulence in conjunction with the vertical temperature profile method developed by Haymond.

The first isotherm pattern utilizes horizontal temperature gradients measured on constant pressure charts. This pattern was observed in connection with one case of moderate turbulence but did not appear in the analysis of cases of smooth air or light turbulence. These criteria which are basically a minor modification of Mitchell's temperature gradients and turbulence relationships are described in Table 2.

TABLE 2. RELATIONSHIP BETWEEN HORIZONTAL TEMPERATURE GRADIENTS AND FLIGHT CONDITIONS

$\leqslant 1.0^{\circ}$C per 30 nautical miles - smooth - very light turbulence

$\leqslant 1.0^{\circ}$C per 20 nautical miles - light turbulence

$\leqslant 1.0^{\circ}$C per 10 nautical miles - moderate turbulence

$> 1.0^{\circ}$C per 10 nautical miles - moderate to severe turbulence

Another horizontal temperature configuration that was observed to occur with one of the two moderate turbulence encounters was the change in isotherm orientation between two successive constant pressure levels. In this case, directional changes in isotherm orientation between two mandatory pressure levels exceeded 45° in the general area in which moderate turbulence was reported. No similar configuration was observed when very light turbulence or smooth flight conditions were encountered. This directional change in orientation in the vertical plane may precede the development of significant temperature inversions at the higher altitudes.

Table 3 summarizes the four categories of horizontal and vertical temperature criteria and the distribution of cases by types of flight conditions from smooth up to and including moderate turbulence.

TABLE 3. RELATIONSHIP BETWEEN FLIGHT CONDITIONS AND TEMPERATURE PATTERNS

	VERTICAL INVERSIONS $\geqslant +1.5^{o}C/1000$ Ft.	HORIZONTAL ISOTHERM GRADIENT	HORIZONTAL ISOTHERM DIRECTIONAL CHANGE	VERTICAL TEMPERATURE CHANGE RATE $\leqslant +1.5^{o}C/1000$ Ft.
	Cases	Cases	Cases	Cases
Smooth - Vry. Lt. Turbc.	--	--	--	5
Lt. Turbc.	2	--	3	1
Mdt. Turbc.	2	1	1	1

Although data from 13 flights were analyzed, two of the three flights in which moderate turbulence was encountered revealed an association between more than one of the temperature criteria.

CONCLUDING REMARKS

Detailed observations of atmospheric behavior and recordings of aircraft data are necessary elements in the development of methods to forecast and detect clear air turbulence. This technique has been used successfully in turbulence research related to the subsonic jet airplane. Understanding at least some of the physical processes in the atmosphere that produce, sustain, and eventually dissipate turbulence is a basic requirement to further success in research of this nature. Multiplicity of aircraft measurements are required to experience the many types of atmospheric conditions that produce smooth as well as turbulent flight conditions. These, in conjunction with the vitally important measurements recorded by meteorological instrumentation, will hopefully contribute to a further understanding and solution of the turbulence problem.

Comparative flights such as were accomplished during this period of research are required to determine the extent of smooth as well as turbulent layers in the atmosphere. It is also necessary to determine the effect of one or more turbulence producing phenomena and their capability of producing both large or small layers as well as areas of turbulence.

Inversions in the troposphere appear to be less important in producing turbulence than in the stratosphere where inversions and encounters of clear air turbulence have displayed a much clearer relationship. Lower stability in the troposphere is a major reason for fewer turbulent inversions. Only comparative flights can provide the detailed flight and meteorological data required to study the similarity between flight conditions in the troposphere and stratosphere. Analysis of data from two or more flight levels can provide additional information on the relationship between horizontal and vertical gradients and flight conditions at each level as well as the dimensions of the affected area.

The refinement of this relationship will hopefully contribute to the successful development of remote sensing devices to detect temperature gradients in the atmosphere utilizing radiometric or other types of electronic instrumentation. The eventual result must be the production of a practical airborne detection system. It must provide sufficient warning to the flight crew to enable them to either avoid completely or at least minimize the effect of the impending turbulence. Furthermore, the detection system must incorporate vertical and possibly horizontal scan capabilities to provide the crew with advice on avoidance maneuvers. However, the detection capabilities of such an instrument must rely on sound physical principles of atmospheric behavior to be successful.

July, 1969
Flight Research & Development
EASTERN AIR LINES, INC.
Miami, Florida

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2. Mitchell, Finis A. and Prophet, David T.: Meteorological Analysis of Clear Air Turbulence in the Stratosphere. Proceedings of the Symposium on Clear Air Turbulence and Its Detection. Boeing Scientific Research Laboratory. The Boeing Company, May, 1969.

3. Ehernberger, L. J.: Atmospheric Conditions Associated With Turbulence Encountered by the XB-70 Airplane Above 40,000 Feet Altitude. NASA TN D-4768, September, 1968.

4. Kadlec, Paul W.: Atmospheric Temperature Gradients Related to Clear Air Turbulence in the Upper Troposphere and Lower Stratosphere. NASA CR-91055, November, 1967.

APPENDIX

RESEARCH FLIGHTS FOR PERIOD
JUNE 25, 1968 - JUNE 1, 1969

DATE	ROUTE	FLT. NO.	FLT. TIMES
6/26/68	MIA - LAX	NAL 51	2200 - 0236Z/27
6/27/68	LAX - SEA	WAL 602	1652 - 1853Z
6/27/68	SEA - LAX	WAL 216	1947 - 2150Z
6/28/68	LAX - SEA	WAL 719	1521 - 1728Z
6/28/68	SEA - LAX	WAL 216	2045 - 2250Z
6/29/68	LAX - MSP	WAL 502	1520 - 1811Z
7/18/68	MIA - LAX	NAL 51	2229 - 0308Z/19
7/19/68	LAX - SLC	WAL 60	1450 - 1606Z
7/19/68	SLC - SFO	UAL 161	1934 - 2053Z
7/19/68	SFO - LAX	UAL 521	2200 - 2251Z
7/20/68	LAX - MIA	NAL 52	1604 - 2040Z
8/16/68	SEA - DEN	UAL 462	1534 - 1738Z
8/16/68	DEN - LAX	UAL 571	1817 - 2101Z
8/16/68	LAX - SEA	UAL 328	2207 - 0007Z/17
8/17/68	SEA - MIA	EAL 95 - 221	1537 - 2217Z
9/9/68	MIA - LAX	NAL 41	1415 - 1859Z
9/10/68	LAX - SEA	UAL 382	1515 - 1715Z
9/10/68	SEA - DEN	UAL 354	1925 - 2126Z
9/10/68	DEN - LAX	UAL 367	2302 - 0057Z/11
9/13/68	LAX - MIA	NAL 42	2005 - 0028Z/14

APPENDIX

DATE	ROUTE	FLT. NO.	FLT. TIMES
10/16/68	MIA - LAX	NAL 41	1415 - 1900Z
10/18/68	LAX - SEA	UAL 382	1515 - 1720Z
10/18/68	SEA - DEN	UAL 354	1925 - 2126Z
10/18/68	DEN - LAX	UAL 367	2310 - 0107Z/19
10/19/68	LAX - MIA	NAL 52	1706 - 2129Z
12/12/68	MIA - LAX	NAL 51	2237 - 0328Z/13
12/12/68	LAX - SEA	UAL 382	1612 - 1809Z
12/13/68	SEA - DEN	UAL 354	2024 - 1718Z
12/13/68	DEN - LAX	CAL 43	0035Z/14 - 0223Z/14
12/14/68	LAX - MIA	NAL 42	2119 - 0140Z/15
12/16/68	MIA - LAX	NAL 51	2244 - 0336Z/17
12/17/68	LAX - SEA	UAL 382	1650 - 1920Z
12/17/68	SEA - DEN	UAL 354	2045 - 2242Z
12/17/68	DEN - LAX	UAL 367	0015Z/18 - 0202Z/18
12/18/68	LAX - MIA	NAL 60	1712 - 2105Z
1/7/69	MIA - LAX	NAL 41	1528 - 2017Z
1/10/69	LAX - MIA	NAL 60	1217 - 2122Z
1/23/69	MIA - LAX	NAL 41	1533 - 2102Z
1/24/69	LAX - MIA	NAL 42	0246Z/25 - 0650Z/25
1/30/69	MIA - LAX	NAL 51	2239 - 0338Z/31
2/1/69	LAX - MIA	NAL 60	1721 - 2126Z

APPENDIX

DATE	ROUTE	FLT. NO.	FLT. TIMES
2/3/69	MIA - LAX	NAL 51	2237 - 0335Z/4
2/4/69	LAX - MIA	UAL 6	1809 - 2233Z
2/4/69	JFK - MIA	EAL 401	0243Z/5 - 0503Z/5
3/19/69	MIA - ORD	EAL 70	2112 - 2347Z
3/20/69	ORD - SFO	UAL 123	1616 - 2037Z
3/20/69	SFO - MIA	NAL 46	2224 - 0342Z/21
4/12/69	MIA - ORD	EAL 72	1534 - 1801Z
4/10/69	ORD - SEA	UAL 147	1912 - 2257Z
4/11/69	SEA - ORD	UAL 150	1712 - 2029Z
4/11/69	ORD - MIA	EAL 73	2324 - 0134Z/12
4/22/69	MIA - ORD	EAL 72	1533 - 1832Z
4/22/69	ORD - SEA	UAL 147	1912 - 2251Z
4/23/69	SEA - ORD	UAL 150	1714 - 2051Z
4/23/69	ORD - MIA	EAL 73	2314 - 0147Z/24